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DATA MINING FOR DOUBLE STARS IN ASTROMETRIC CATALOGS

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ABSTRACT

The US Naval Observatory has mined over 140 astrometric catalogs, including the Astrographic Catalogue and the Two Micron All Sky Survey, for measures of double stars. This resulted in 114,218 new measures of 47,007 different systems spanning 110 years; these are now included in the Washington Double Star catalog (WDS). This is the single largest data set ever added to the WDS. The measures are typically of wider pairs, most between 4″ and 30″; thus, their value in aiding orbit determination is limited. However, they have proven invaluable in the verification of systems and the determination of rectilinear motions of systems.

Key word: binaries: visual

Online material: machine-readable tables

1. INTRODUCTION

Since the 1960s, the United States Naval Observatory (USNO) has been heavily involved in converting astrometric-quality star catalogs to machine-readable form, primarily for use in determining high-precision proper motions, since this requires utilization of many sources over as long a time base as possible. This data set is called the Washington Fundamental Catalog (WFC), although no catalog was ever released under that name. The WFC contains data from 144 ground-based catalogs, most observed with transit circles or astrographs, totaling over 8 million star positions, some dating as early as the late 1800s. A list of WFC source catalogs is given in Table 5 of the *Guide to the Tycho-2 Catalogue*.[1] All WFC data were reduced to the International Celestial Reference System using the *Hipparcos* catalog (Perryman et al. 1997). Two notable results of the WFC were the generation of proper motions for Tycho-2 (Høg et al. 2000a, 2000b) and the Second US Naval Observatory CCD Astrograph Catalog (UCAC2; Zacharias et al. 2000). It was realized that in addition to being a source of information for proper motions, the WFC contains a wealth of double star measures that could go into the Washington Double Star catalog (WDS; Mason et al. 2001).[2]

During the course of extracting double star measures from the WFC, the final release of the Two Micron All Sky Survey (2MASS; Cutri et al. 2003) was made. It was realized that this data set also contains a wealth of double star information; therefore, using the same pair identification methodology, measures from the 2MASS Point Source Catalog[3] were extracted and added to the WDS.

This paper details the extraction process and provides tabular data for the individual measures, as well as giving important statistics. Section 2 explains the method used to match the input data to the WDS. Section 3 discusses the errors of the measures. Section 4 discusses newly identified double systems in the WFC, while § 5 describes the contributions of this new set of data to double star science.

[1] Tycho-2 CD-ROM and http://www.astro.ku.dk/~cf/CD/docs/guide.pdf.

[2] See http://ad.usno.navy.mil/wds/wds.html for the most current version.

[3] 2MASS Point Source Catalog, 2003 all-sky release (Cutri et al. 2003). See http://pegasus.phast.umass.edu.

2. EXTRACTION OF DATA

The WFC data set, having been designed to be used in proper motions work, was first precessed to J2000.0. Double star observations, on the other hand, are published at the equator and equinox for the epoch of observation. Therefore, the first step in the matching/extraction processes was to precess the WFC positions back to their original observation dates. The WFC epoch was computed as the mean of the right ascension and declination epochs for each star.[4] Since the measures are relative position angles and separation (not position on the sky), the adjustment due to precession is small for most of the systems; however, it can grow considerably for the older catalogs and for systems near the poles. An example is illustrated in Figure 1.

Following the precession of the data to the epoch of observation, a positional match was performed between the catalog positions in the WFC and the WDS. This match used a search radius of 120″ from each WDS entry. Subsequently, the position angle and separation parameters of any two WFC stars within this radius were compared with the same parameters in the WDS. As this filter is for a correct match, if the position angle difference was less than 30° and the separation change was less than 30%, then the WFC system was selected as a match.

The actual extraction of data was done in three phases. The first extraction, done in late 2001, resulted in 36,547 measures. As double star positions were improved or additional doubles were found either in historical literature or by other observing programs, it was possible to do another match; this was done in late 2003, resulting in an additional 18,755 measures. Finally, following release of the 2MASS catalog, a similar matching procedure was used to identify double star measures in that catalog. The density of the 2MASS catalog posed a challenge, as there could be many pairs within a given large search window matching the general relative astrometry of the pair. Determining precise coordinates in earlier iterations of the project allowed the shrinking of these windows and, thus, the number of false positives. Matching with 2MASS and rematching with the other catalogs resulted in 58,916 more measures. This exercise is appropriate whenever large astrometric catalogs are added and will

[4] In some cases the mean epochs of the two coordinates differ slightly. See footnote 5.

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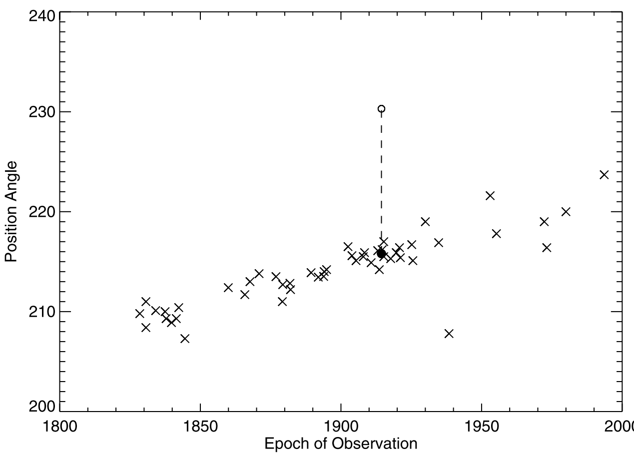

FIG. 1.—Position angle vs. time for the measures of the double star STF 93 AB (WDS 02318+8916). Classical double star measures—all referred to their mean equator and equinox of observation—are represented with a cross. The calculated position angle from the Second Greenwich Catalog (Dyson 1935) precessed to J2000.0 is given as an open circle. Precessing the position back to equator and equinox of the observation (*filled circle*) changes the position angle significantly, where it matches contemporaneous measures quite well.

be repeated when the final UCAC release is matched and as warranted by the discovery of new wide binary systems.

Table 1 presents a listing of the astrographic and transit circle catalogs contributing double star measures. The catalog code is given in column (1), with the catalog name and reference given in columns (2) and (3). Catalogs coded with the lead "WFC" designation are photographic catalogs, whereas those with the lead "WFD" designation contain transit circle observations. Column (4) lists the number of contributing double star measures. It is worth noting that the vast majority of new measures are from two sources, the Astrographic Catalogue (AC; Urban et al. 1998) and the 2MASS Point Source Catalog.

A histogram of the epochs of observation is presented in Figure 2. As expected, this figure illustrates features in the AC and 2MASS. The AC was observed over several decades in the late 1800s and early 1900s and is the major source of pre-1930 data. The spike in the number of observations near the year 2000 is due primarily to the 2MASS catalog.

A histogram illustrating the separation coverage is given in Figure 3. The decrease in number at closer and wider separations is for two different reasons. At closer separations the inability to resolve closer companions is not unexpected given the limitations of short focus astrometry and the photographic process. In fact, in the compilation of the AC, measures of two "stars" that were closer than $2''$ were usually treated as a duplicate measure of a single star and combined. In addition, transit circle programs routinely avoided close doubles because they generally made poor reference stars. At wider separations the decrease is due to the lack of known binaries at these relative distances.

Table 2 presents all 114,218 measures. In this table, columns (1) and (2) identify the system by providing the epoch 2000 coordinate and discovery designation. Columns (3)–(5) give the mean values for epoch of observation[5] (expressed as fractional Besselian year), the position angle (in degrees), and the separation (in arcseconds). Column (6) indicates the number of observations contained in the means, while column (7) lists the appropriate source of the data from the list in Table 1. Column (8) lists the aperture of the telescope used in the observation, while the code in column (9) indicates the observing method. Column (10) is reserved for notes.

3. ERRORS OF MEASUREMENT

As an assessment of the quality of WFC measures, they have been compared to systems with calibration-quality orbits (Hartkopf et al. 2001). While these systems contain many definitive orbits, they also contain a like number of wider, long-period systems whose orbits, while describing the complete motion inexactly, provide perfectly reasonable ephemerides over the observation dates. Two examples of these are given in Figures 4 and 5. The full list of residuals to calibration systems is presented in Table 3. Columns (1)–(7) are the same as in Table 2 described above. Columns (8) and (9) give the $O - C$ (observed minus calculated) orbit residuals (in θ and ρ) to the orbit referenced in column (10).

Table 4 lists the mean orbit residuals for the different catalogs cited in Table 3. Column (1) lists the catalog code, while column (2) provides the number of measures from Table 2 included in the mean. Columns (3) and (4) give the mean $O - C$ orbit residual. Column (5) lists notes. Typically, these indicate when residuals have been determined from a subset of the wider ($\rho > 5''\!.0$) data. Means of astrograph, transit circle, and all data are also provided. The systematic overestimating of very close systems that has been noted for other techniques (Worley 1981) is also seen here. When close systems are measured, at separations less than about $10''$ the error can be considerable, as shown in Figure 6. While these measures with larger errors are still of value in systems with few measures, their value in systems with many measures (especially those with contemporaneous double star observations) is of limited value. As is shown in Figure 7, the error has gone up slightly over the past century. However, comparison with Figure 6 indicates that these large-error systems are also those that are closest.

4. NEW WFC DOUBLES

The matching of the astrometric catalogs was done against the WDS in an effort to obtain more measures. However, in the match of known doubles additional pairs were flagged as possible new systems if they met one of two possible criteria: (1) the magnitude and separation fell within Aitken's (1932) proximity parameter; or (2) they were closer than $10''$. Modifications of Aitken's parameter for distinguishing between optical and physical pairs have been used (Rossiter 1955) in other surveys, and while it has significant limitations it is useful to highlight possible physical pairings of bright stars. The proximity limit was used because pairs closer than this may cause difficulties in the event of blended images. While many of these may be optical rather than physical, their proximity is the compelling factor, and these are pointedly "WFC doubles," not "WFC binaries." Identification of new pairs using these methods was not done with the 2MASS data (and will not be attempted with other deep catalogs, e.g., UCAC3) as the catalogs are so dense and deep the pairings identified by these techniques are more likely to be optical. While there are no doubt physical pairs contained within these catalogs, more traditional methods of identifying binaries (rather than doubles) such as Keplerian motion or common proper motion need to be used (see, e.g., Greaves 2004).

A total of 280 systems not previously resolved had more than one WFC measure in an initial inspection and were added to the

[5] For transit circle catalogs these epochs are usually different, and the precision of the mean epoch presented in the table is dependent on the standard deviation of the individual epochs. For example, if the standard deviation is less than 0.1 yr, then the mean epoch is expressed in units of 0.01 yr.

TABLE 1

Number of Double Star Measures

Catalog Code (1)	Catalog Description (2)	Catalog Reference (3)	Number of Measures (4)
WFC			
WFC1939	Yale Observatory (−10 to −14)	Schlesinger & Barney (1939)	76
WFC1940a	Yale Observatory (−14 to −18)	Schlesinger & Barney (1940)	62
WFC1940b	Yale Observatory (−18 to −20)	Schlesinger & Barney (1940)	29
WFC1943a	Yale Observatory (−20 to −22)	Schlesinger & Barney (1943)	10
WFC1943b	Yale Observatory (−27 to −30)	Schlesinger & Barney (1943)	51
WFC1943c	Yale Observatory (−22 to −27)	Schlesinger & Barney (1943)	62
WFC1945a	Yale Observatory (−06 to −10)	Barney (1945)	57
WFC1945b	Yale Observatory (−02 to −06)	Barney (1945)	45
WFC1947	Yale Observatory (+15 to +20)	Barney (1947)	94
WFC1948	Yale Observatory (+09 to +15)	Barney (1948)	125
WFC1949	Yale Observatory (+01 to +05)	Barney (1949)	107
WFC1950a	Paris Observatory (+17 to +25)	Baillaud (1950)	12
WFC1950b	Yale Observatory (+01 to −02)	Barney (1950)	33
WFC1950c	Yale Observatory (+05 to +09)	Barney (1950)	95
WFC1954a	Cape Photographic Catalog (−30 to −35)	Jackson & Stoy (1954a)	51
WFC1954b	Cape Photographic Catalog (−35 to −40)	Jackson & Stoy (1954b)	84
WFC1954c	Cape Photographic Catalog (−52 to −56)	Jackson & Stoy (1955)	79
WFC1954d	Yale Observatory (+20 to +30)	Barney (1953, 1954)	177
WFC1954e	Yale Observatory (+85 to +90)	Barney & van Woerkom (1954)	5
WFC1958a	AGK2 North of $-2\fdg5$ (Bergedorf)	Schorr & Kohlschuetter (1958)	1666
WFC1958b	AGK2 North of $-2\fdg5$ (Bonn)	Schorr & Kohlschuetter (1958)	1057
WFC1958c	Cape Photographic Catalog (−56 to −60)	Jackson & Stoy (1958)	51
WFC1958d	Cape Photographic Catalog (−60 to −64)	Jackson & Stoy (1958)	76
WFC1959	Yale Observatory (+50 to +60)	Barney et al. (1959)	242
WFC1966a	Cape Photographic Catalog (−64 to −68)	Stoy (1966)	71
WFC1966b	Cape Photographic Catalog (−68 to −72)	Stoy (1966)	53
WFC1966c	Cape Photographic Catalog (−72 to −76)	Stoy (1966)	32
WFC1966d	Cape Photographic Catalog (−76 to −80)	Stoy (1966)	30
WFC1967	Yale Observatory (−30 to −35)	Hoffleit (1967)	85
WFC1968a	Cape Photographic Catalog (−80 to −89)	Stoy (1968a)	24
WFC1968b	Yale Observatory (−35 to −40)	Hoffleit (1968)	93
WFC1970	Yale Observatory (−40 to −50)	Hoffleit (1970)	152
WFC1971	Yale Observatory (−70 to −90)	Lu (1971)	210
WFC1975	AGK3 North of $-2\fdg5$	Heckmann & Dieckvoss (1975)	2805
WFC1983a	Sydney Observatory (−48 to −54)	Eichhorn et al. (1983)	173
WFC1983b	Sydney Observatory (−51 to −63.5)	King & Lomb (1983)	129
WFC1983c	Yale Observatory (−60 to −70)	Fallon & Hoffleit (1983)	121
WFC1992	CPC2	Zacharias et al. (1992)	1163
WFC1994	FOKAT	Bystrov et al. (1994)	576
WFC1998	Astrographic Catalog 2000	Urban et al. (1998)	54242
WFC1999	Twin Astrographic Catalog	Zacharias & Zacharias (1999)	2668
Total WFC	...	...	66973
WFD			
WFD1889	Second Melbourne Catalog	Ellery & White (1889)	7
WFD1904	Kat. der Astron. Gesell.	de Ball (1904)	76
WFD1906a	Cape General Catalog	Gill (1906)	11
WFD1906b	Kat. der Astron. Gesell.	Becker (1906)	47
WFD1907	Lick Observatory	Tucker (1907)	15
WFD1908a	Bonn University	Küstner (1908)	1
WFD1908b	Kat. der Astron. Gesell.	Skinner (1908)	73
WFD1909	Greenwich Second Nine Year Catalog	Christie (1909)	127
WFD1914	Abbadia Observatory (Algiers zone)	Abbadia Obs. (1914)	123
WFD1915a	Abbadia Observatory (Paris zone)	Abbadia Obs. (1915)	206
WFD1915b	Cape Fundamental Catalog	Gill & Hough (1915)	1
WFD1916	Berlin-Babelsberg (+79 to +90)	Freundlich (1916)	13
WFD1917a	Abbadia Observatory (San Fernando zone)	Abbadia Obs. (1917)	9
WFD1917b	Third Melbourne Catalog	Ellery & Baracchi (1917)	21
WFD1918a	Albany Catalog	Boss (1910)	162
WFD1918b	Albany Catalog	Boss & Roy (1918)	31
WFD1919	La Plata A Catalog	Delavan (1919)	36
WFD1920a	Second Cape Fundamental Catalog	Hough (1920)	3

TABLE 1—*Continued*

Catalog Code (1)	Catalog Description (2)	Catalog Reference (3)	Number of Measures (4)
		WFD	
WFD1920b...........	Greenwich Catalog	Dyson (1920)	166
WFD1920c...........	USNO	Eichelberger (1920)	43
WFD1921.............	Bonn University	Küstner & Monnichmeyer (1921)	14
WFD1923.............	Berlin-Babelsberg (+31 to +40)	Prager (1923)	10
WFD1924a...........	Alger Observatory	Rambaud (1924)	44
WFD1924b...........	La Plata C Catalog	Martinez (1924)	14
WFD1925.............	Lick Observatory	Tucker (1925)	2
WFD1926a...........	Konigsberg Observatory	Przybyllok (1926)	5
WFD1926b...........	Lund Observatory	Gyllenberg (1926)	111
WFD1927a...........	Bonn University	Küstner (1927)	1
WFD1927b...........	Munich	Oertel (1927)	75
WFD1927c...........	Munich	Oertel (1927)	86
WFD1928a...........	First Bergedorf	Dolberg (1928)	120
WFD1928b...........	First Cape Catalog	Jones (1928)	33
WFD1928c...........	Leiden Observatory	Hins (1928)	1
WFD1928d...........	San Luis Catalog	Boss & Boss (1928)	357
WFD1929a...........	La Plata B Catalog	Aguilar & Dawson (1929)	19
WFD1929b...........	Nice Observatory	Fayet (1929)	11
WFD1929c...........	Paris Observatory	Chatelu (1929)	130
WFD1931.............	Albany Catalog	Boss (1931)	1056
WFD1933a...........	Pulkovo Observatory	Morin (1933)	3
WFD1933b...........	USNO	Morgan (1933)	32
WFD1934a...........	Leiden Observatory	Hins (1934)	2
WFD1935.............	Second Greenwich Catalog	Dyson (1935)	102
WFD1936.............	La Plata D Catalog	Manganiello (1936)	23
WFD1937.............	Toulouse Observatory	Paloque (1937)	4
WFD1938.............	La Plata F Catalog	Martinez (1938)	46
WFD1939.............	Madison Catalog	Flint & Roy (1939)	6
WFD1940.............	Pulkovo Observatory	Seraphimoff (1940)	6
WFD1941.............	Toulouse Observatory	Paloque (1941)	102
WFD1943.............	La Plata Observatory	Martinez (1943)	16
WFD1947.............	La Plata E Catalog	Tapia (1947)	2
WFD1948.............	USNO	Morgan & Scott (1948)	31
WFD1949a...........	Second Cape Catalog	Jackson (1949)	97
WFD1949b...........	USNO	Watts & Adams (1949)	22
WFD1951a...........	Third Cape Catalog	Jackson (1951)	51
WFD1951b...........	Lund Observatory	Reiz (1951)	9
WFD1952.............	USNO	Watts et al. (1952)	9
WFD1953.............	First Cape Catalog	Jackson (1953)	120
WFD1954a...........	Cape Photographic Standard (−35 to −40)	Jackson & Stoy (1954b)	2
WFD1954b...........	Cordoba D Catalog	Guerin & Bobone (1954)	87
WFD1958a...........	Cape Photographic Standard (−56 to −64)	Jackson & Stoy (1958)	3
WFD1958b...........	Cape Photographic Standard (−56 to −64)	Jackson & Stoy (1958)	3
WFD1959.............	La Plata Observatory	Martinez (1959)	156
WFD1963.............	System of Fundamental Proper Motions	Scott (1963)	6
WFD1964.............	USNO	Adams & Bestul (1964)	24
WFD1966a...........	Cape Photographic Standard (−64 to −68)	Stoy (1966)	1
WFD1966b...........	Cape Photographic Standard (−68 to −80)	Stoy (1966)	1
WFD1968a...........	Second Cape Catalog	Stoy (1968b)	88
WFD1968b...........	Cape Photographic Standard (−80 to −90)	Stoy (1968a)	1
WFD1969.............	First Greenwich Catalog	Woolley (1969)	94
WFD1973.............	Cordoba E Catalog	Bobone (1973)	5
WFD1985.............	Carlsberg Meridian Catalog	CUO, RGO, ROA (1985)[a]	567
WFD1988.............	Perth Observatory	Harwood (1988)	60
WFD1989.............	Tokyo Photoelectric Meridian Catalog	Yoshizawa & Suzuki (1989)	30
WFD1990.............	SRS Catalog	Smith et al. (1990)	3
WFD1997.............	USNO	Holdenried & Rafferty (1997)	168
WFD2000.............	USNO (pole-to-pole)	Rafferty & Holdenried (2000)	65
WFD9999.............	Heidelberg Zodiacal 50	G. Wycoff 2005, unpublished	8
Total WFD	...	...	5321
TMA2003.............	2MASS Catalog	2003 All-Sky Release	41924
All	...	...	114218

[a] Copenhagen University Observatory, Royal Greenwich Observatory, and Instituto y Observatorio de Marina.

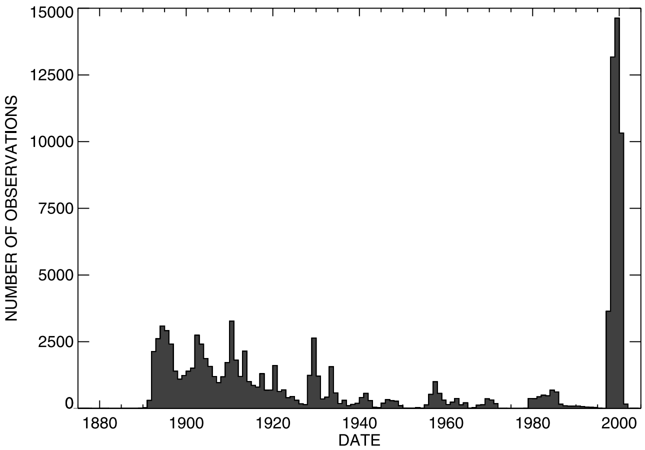

Fig. 2.—Histogram plot of the number of WFC measures plotted vs. time in 1 yr bins. The majority of late 19th and early 20th century data are from the Astrographic Catalog (Urban et al. 1998). The spikes in the 1960s and 1980s are primarily due to the Second Cape Photographic Catalog (CPC2; Zacharias et al. 1992) and the Twin Astrographic Catalog (TAC; Zacharias & Zacharias 1999), and the most recent large contribution is from 2MASS (Cutri et al. 2003).

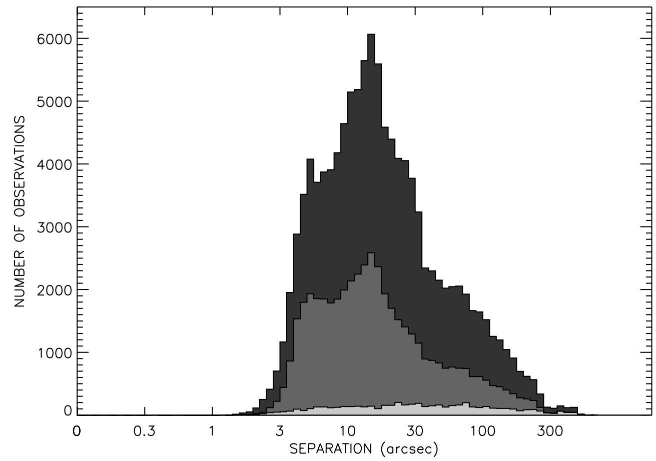

Fig. 3.—Histogram plot of all WFC double star measures vs. separation. The median separation is 14″.02. *Light gray histogram*, transit circle measures (code = WFD, median $\rho = 27''.51$); *middle gray histogram*, measures from 2MASS (code = TMA, median $\rho = 12''.23$); *darkest gray histogram*, measures from astrographs or similar instruments (code = WFC, median $\rho = 14''.88$).

WDS. Systems with only one measure were not added, as the uncertainty in quality of the various techniques made their veracity subject to doubt. The current WDS entries for these systems are provided in Table 5. In this table, column (1) gives the abbreviated J2000.0 coordinates, which also serve as the WDS designation. Column (2) provides the discovery designation. The WFC designation given in this column is only approximately sequential in right ascension due to the timing of their confirmations. Columns (3) and (4) give the dates of first and last observation, while column (5) gives the number of observations. The position angles of the binary on the first and last observation dates are given in columns (6) and (7). The separations in arcseconds for these observations are given in columns (8) and (9). Finally, columns (10) and (11) give the magnitude of the primary and secondary stars, respectively. Magnitudes given to a tenth of a magnitude are provided by the source catalog. For photographic catalogs (coded with prefix "WFC" in Table 1), these can be taken as approximately *B*. For visual catalogs (those coded with prefix "WFD" in Table 1), these can be taken as approximately *V*. When given to the nearest hundredth of a magnitude, the source of the magnitude is the V_T magnitude of Tycho-2.

Stars with entries in the Tycho-2 catalog (Høg et al. 2000a, 2000b) have been inspected to make sure their proper motions are not incompatible. In no case was this found to be true. Again, the accuracy in the listing of magnitudes in Table 5 indicates which new WFC doubles have proper motions contained in Tycho-2.

In addition to these new systems with multiple epochs, there were a total of 153 "single epoch" WFC stars. While these represent measures of questionable detections, they are being retained until inspection either at USNO or at outside institutions. While the greatest hope for these systems is possibly the UCAC project (Zacharias et al. 2000), 69 systems have been confirmed by the Tycho Double Star reduction project (Fabricius et al. 2002) and 14 by 2MASS. Six others were confirmed with the USNO speckle camera and 26 inch (0.7 m) refractor in the spring of 2001 (Mason et al. 2002), and one in 2002 (Mason et al. 2004). Additional single-epoch new doubles will be added to the WDS as they are confirmed.

5. CONTRIBUTIONS TO DOUBLE STARS

This compilation of data added to the WDS represents the single largest data set added; 16% of the mean positions in the WDS come from this work, and they represent 46% of the known systems. However, they are the wider, typically slow-moving systems. For most double stars it takes quite a few measures spanning several years to classify them as having motion that is either Keplerian or rectilinear. So, while the data set is large and helpful in cases of verification and linear proper motions, its value in the case of orbit systems is severely limited. A summary of the WFC contributions to double star measures is presented in Table 6. In any event, 109 systems, including those listed in Table 3, have orbital determinations. The greater contribution is expected to come for systems with linear solutions (i.e., differential proper motion), which is expected to be significant. A total of 1141 systems have these types of solutions (W. T. Hartkopf et al. 2006, in preparation).

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TABLE 2

Measurements of Double Stars

WDS or α, δ (J2000.0) (1)	Discovery Designation (2)	Epoch (3)	θ (deg) (4)	ρ (arcsec) (5)	n (6)	Catalog Code (see Table 1) (7)	Aperture (inches) (8)	Method (9)	Notes (10)
00000+3852	BU 860	1999.75	107.8	6.34	1	TMA2003	51	F	K
00000+4004	ES 2543	1999.75	252.3	4.51	1	TMA2003	51	F	K
00001+5400	ES 704	1999.71	116.0	4.41	1	TMA2003	51	F	K
00002−2519	COO 273	1910.75	9.7	9.028	1	WFC1998	13	G	
00002−2519	COO 273	1910.84	11.8	8.484	1	WFC1998	13	G	
00002−2519	COO 273	1933.73	12.2	8.510	1	WFC1943c	05	G	
00002−2519	COO 273	2000.71	10.4	8.50	1	TMA2003	51	F	K
00003−0654	LDS 6079	1998.77	1.3	158.39	1	TMA2003	51	F	K
00003+1642	HJ 318	1999.83	61.8	26.51	1	TMA2003	51	F	K
00003+5651	CTT 1	1906.89	90.1	49.423	1	WFC1998	13	G	
00003+5651	CTT 1	1908.83	91.6	49.549	1	WFC1998	13	G	
00003+5651	CTT 1	1917.93	91.4	48.608	1	WFC1998	13	G	
00003+5651	CTT 1	1999.71	92.8	46.74	1	TMA2003	51	F	K
00004+0830	BU 732	2000.72	151.7	5.86	1	TMA2003	51	F	K
00004+0830	BU 732 AC	1897.80	143.0	152.220	1	WFC1998	13	G	

Notes.—(K): Infrared measure, i.e., 2MASS. Table 2 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

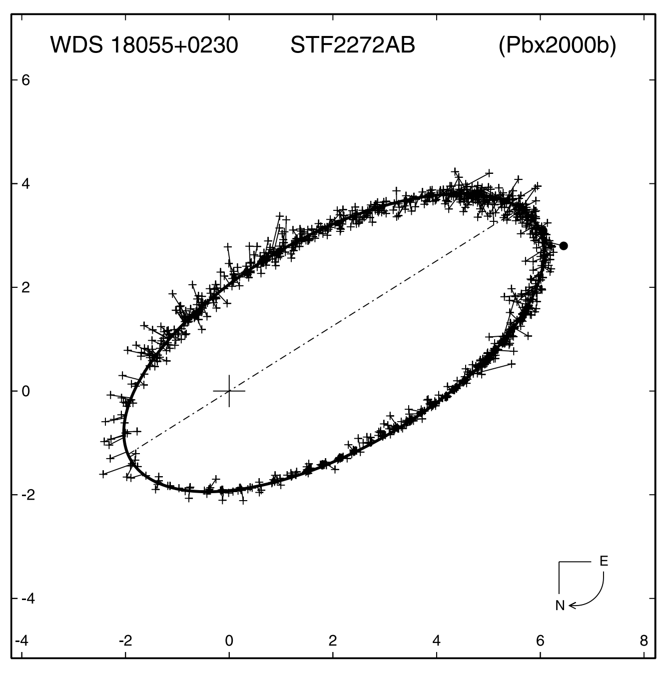

Fig. 4.—All double star measures of STF 2272 AB (WDS 18055+0230) plotted against the definitive orbit of Pourbaix (2000). The two filled circles at the widest separation are the WFC measures. All other double star measures are shown by plus signs. $O-C$ lines connect data points with their predicted positions on the orbit. The broken line is the line of nodes, and the axes of the figure are in arcseconds. The direction of motion is indicated in the lower right corner. Position angles are measured from north through east.

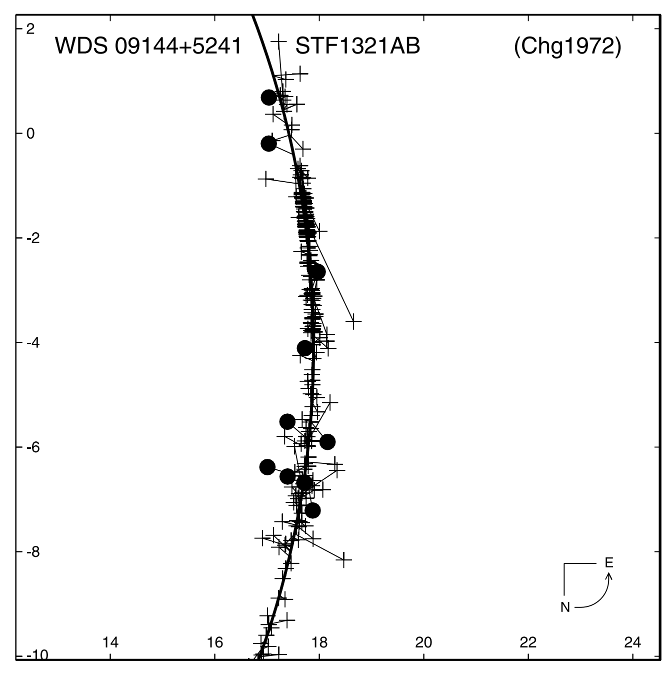

Fig. 5.—All double star measures of STF 1321 AB (WDS 09144+5241) plotted against the provisional (but still calibration-quality) orbit of Chang (1972). In this case only the portion of the orbit (48° or 13% of a period) with data is plotted. As noted in Table 3, this system has the greatest number of WFC measures. All symbols are as in Fig. 4.

TABLE 3
WFC Measures of Calibration-Quality Orbits

WDS or α, δ (J2000.0) (1)	Discovery Designation (2)	BY (3)	θ (deg) (4)	ρ (arcsec) (5)	N (6)	Catalog Code (see Table 1) (7)	$O-C_\theta$ (deg) (8)	$O-C_\rho$ (arcsec) (9)	Orbit Reference (10)
00057+4549	STT 547	1915.80	142.4	5.235	1	WFD1931	2.1	0.38	Popovic & Pavlovic (1996)
		1929.78	147.0	6.014	1	WFC1958a	−1.9	0.86	
		1956.92	155.3	4.360	1	WFC1975	−7.7	−1.30	
		1998.84	181.0	6.03	1	TMA2003	−0.6	0.05	
01398−5612	DUN 5	1910.20	218.4	7.912	4	WFD1928d	0.7	−0.37	van Albada (1957)
		1920.80	220.3	9.252	1	WFC1998	7.1	0.38	
		1938.01	208.2	8.948	8	WFD1953	1.1	−0.75	
		1946.90	201.1	10.221	1	WFC1958c	−3.2	0.15	
		1999.82	189.9	11.15	1	TMA2003	−0.7	−0.37	
02020+0246	STF 202	1913.60	303.2	2.824	1	WFD1931	−10.9	0.18	Scardia (1983)
02442+4914	STF 296	1999.80	304.8	20.52	1	TMA2003	0.8	0.48	Hopmann (1958)
03368+0035	STF 422	1899.90	244.7	5.645	2	WFD1918b	−3.4	−0.73	Hopmann (1964
		1908.98	250.5	7.475	1	WFC1998	0.4	1.07	
05364+2200	STF 742	1902.7	261.8	4.075	3	WFD1915a	1.4	0.41	Hopmann (1973)
		1915.07	259.1	4.392	2	WFD1928a	−3.1	0.67	
		1934.8	258.0	3.594	3	WFD1969	−7.1	−0.22	
		1980.69	270.8	4.227	5	WFD1997	−0.4	0.21	
		1997.85	273.0	3.59	1	TMA2003	−0.4	−0.49	
07201+2159	STF 1066	1980.24	223.0	6.099	8	WFD1997	1.6	0.01	Hopmann (1960)
08122+1739	STF 1196 AB-C	1907.0	112.1	5.951	3	WFD1929c	−4.7	0.45	Heintz (1996)
09144+5241	STF 1321	1915.10	69.1	18.931	1	WFD1931	0.2	−0.02	Chang (1972)
		1917.7	69.2	18.166	4	WFD1926a	−0.4	−0.73	
		1918.19	69.1	18.591	1	WFD1925	−0.6	−0.30	
		1919.46	67.8	19.274	2	WFD1933b	0.1	0.24	
		1925.95	72.2	18.244	6	WFD1935	0.5	−0.50	
		1930.03	71.8	19.093	1	WFC1958a	−1.0	0.43	
		1947.01	76.8	18.195	1	WFC1959	−0.6	−0.14	
		1958.11	81.5	18.164	1	WFC1975	1.0	0.06	
		1986.02	89.3	17.035	4	WFD1985	0.6	−0.48	
		1998.93	92.3	17.05	1	TMA2003	−0.3	−0.18	
11182+3132..................	STF 1523	1915.65	108.4	3.873	1	WFD1931	−4.9	0.79	Mason et al. (1995)
12160+0538	STF 1621	1914.9	139.1	2.511	1	WFD1928a	−1.9	0.40	Söderhjelm (1999)
13550−0804	STF 1788	1980.04	96.0	3.503	8	WFD1997	1.8	0.13	Hopmann (1970)
		1999.16	97.7	2.75	1	TMA2003	0.2	−0.74	
14131+5520	STF 1820	1920.5	84.3	2.602	2	WFD1928a	−0.6	0.38	Kiyaeva et al. (1998)
14575−2125	H28	1933.40	298.3	19.928	1	WFC1943a	−0.4	0.15	Hale (1994)
		1938.80	300.1	20.310	8	WFD1953	0.7	0.10	
		1939.4	307.4	25.952	4	WFD1948	8.0	5.69	
		1970.54	303.0	22.631	4	WFC1992	0.0	−0.03	
		1985.1	306.4	23.359	3	WFC1994	2.0	−0.36	
16147+3352	STF 2032	1890.61	202.8	4.810	3	WFD1917b	−4.7	0.79	Scardia (1979)
		1910.3	214.5	5.317	1	WFD1928d	−1.1	0.57	
		1912.3	221.8	5.597	1	WFD1931	5.6	0.78	
		1993.3	236.7	7.704	8	WFD2000	1.9	0.82	
		1994.54	236.1	6.887	6	WFD2000	1.1	−0.02	
		1998.26	236.2	6.25	1	TMA2003	0.6	−0.73	
17053+5428	STF 2130	1913.50	130.6	2.785	1	WFD1931	−1.5	0.46	Heintz (1981)
17153−2636	SHJ 243	1929.3	182.9	3.660	4	WFD1949b	5.4	−0.59	Irwin et al. (1996)
		1934.34	178.0	4.699	4	WFD1951a	3.0	0.43	
		1938.88	172.1	4.910	8	WFD1953	−0.8	0.62	
		1940.6	175.9	4.829	9	WFD1948	3.9	0.54	
		1980.44	158.2	5.312	8	WFD1997	4.1	0.70	
18055+0230	STF 2272	1935.7	117.4	6.798	6	WFD1969	−1.1	0.06	Pourbaix (2000)
		1939.14	113.8	7.031	8	WFD1953	−1.8	0.32	
18443+3940	STF 2383 Cc-D	1905.00	128.2	2.504	15	WFD1927b	3.3	0.18	Docobo & Costa (1984)
		1912.80	117.0	2.708	1	WFD1931	−4.5	0.40	
		1980.8	87.2	3.308	7	WFD1997	−3.6	1.01	

TABLE 3—*Continued*

WDS or α, δ (J2000.0) (1)	Discovery Designation (2)	BY (3)	θ (deg) (4)	ρ (arcsec) (5)	N (6)	Catalog Code (see Table 1) (7)	$O - C_\theta$ (deg) (8)	$O - C_\rho$ (arcsec) (9)	Orbit Reference (10)
19121+4951	STF 2486	1901.54	217.6	9.837	1	WFC1998	0.0	0.50	Hale (1994)
		1902.54	223.1	9.958	1	WFC1998	5.6	0.64	
		1909.	205.7	11.383	2	WFD1921	−11.2	2.19	
		1914.10	220.3	9.313	1	WFD1931	3.9	0.21	
		1920.2	217.5	9.139	2	WFD1928a	1.7	0.15	
		1928.4	207.6	9.653	4	WFD1935	−7.4	0.82	
		1929.65	216.3	8.576	1	WFC1958a	1.5	−0.24	
		1957.57	209.8	7.891	1	WFC1975	−2.1	−0.40	
		2000.32	206.2	7.40	1	TMA2003	−0.2	−0.11	
20462+1554	STF 2725	1903.80	11.0	5.326	1	WFC1998	8.7	0.20	Hopmann (1973)
		1913.5	0.5	5.513	1	WFD1931	−2.8	0.28	
		1914.58	6.6	5.133	2	WFD1928a	3.2	−0.11	
		1998.35	9.9	6.02	1	TMA2003	−0.7	−0.04	
20467+1607	STF 2727	1913.5	270.9	11.525	1	WFD1931	1.0	0.73	Hale (1994)
		1934.20	270.6	10.266	7	WFD1969	1.5	−0.19	
		1939.78	268.8	10.767	1	WFC1947	0.0	0.41	
		1940.67	267.6	10.756	8	WFD1953	−1.2	0.41	
		1992.	262.4	9.640	7	WFD2000	−3.9	0.22	
21069+3845	STF 2758	1928.86	134.8	24.450	1	WFC1998	0.2	−0.52	Kisselev et al. (1997)
		1931.87	136.6	25.240	1	WFC1998	1.2	−0.02	
		1957.56	140.9	27.453	1	WFC1975	−0.6	−0.12	
		1980.07	144.0	29.130	8	WFD1997	−2.2	−0.24	
		1998.47	149.6	30.63	1	TMA2003	−0.0	−0.02	
21441+2845	STF 2822	1915.60	109.2	2.043	1	WFD1931	−22.7	0.37	Heintz (1995)
22038+6438	STF 2863	1901.1	282.4	7.015	5	WFD1909	1.0	0.15	Zeller (1965)
		1915.20	280.1	7.375	1	WFD1931	−0.2	0.30	
		1994.80	275.5	7.960	4	WFD2000	0.6	−0.20	
22266−1645	SHJ 345	1895.30	307.1	8.158	2	WFD1908b	−0.8	0.99	Hale (1994)
		1904.64	313.2	7.418	4	WFD1920c	3.9	0.66	
		1914.20	312.6	6.846	1	WFD1931	1.8	0.51	
		1928.65	312.6	5.617	6	WFD1949a	−1.1	−0.03	
		1929.09	313.0	5.431	4	WFD1949b	−0.8	−0.20	
		1939.39	317.5	5.623	8	WFD1953	1.1	0.51	
		1979.62	340.2	3.453	8	WFD1997	4.7	0.57	
23595+3343	STF 3050	1915.70	221.2	2.106	1	WFD1931	−6.0	0.08	Starikova (1977)

TABLE 4

Mean Catalog Errors of Calibration-Quality Binaries

Catalog Code (see Table 1) (1)	N (2)	$O - C_\theta$ (deg) (3)	$O - C_\rho$ (arcsec) (4)	Notes (5)
WFC1943a	1	−0.4	0.15	
WFC1947	1	−0.0	0.41	
WFC1958a	3	−0.5 ± 1.4	0.35 ± 0.45	
WFC1958c	1	−3.2	0.15	
WFC1959	1	−0.6	−0.14	
WFC1975	4	−2.4 ± 3.3	−0.44 ± 0.52	1
WFC1992	1	−0.0	−0.03	
WFC1994	1	2.0	−0.36	
WFC1998	7	3.3 ± 3.4	0.32 ± 0.47	
All astrographs	20	0.5 ± 3.5	0.09 ± 0.52	2
WFD1908a	1	−11.9	2.19	
WFD1909	1	1.0	0.15	
WFD1915a	1	1.4	0.41	3
WFD1917b	1	−4.7	0.79	
WFD1918b	1	−3.4	−0.73	
WFD1920c	1	3.9	0.66	
WFD1921	1	−1.2	0.99	
WFD1925	1	−0.6	−0.30	
WFD1926a	1	−0.4	−0.73	
WFD1927b	1	2.6	0.18	
WFD1928a	5	−0.1 ± 2.3	0.30 ± 0.26	4
WFD1928d	2	−0.2 ± 0.9	0.10 ± 0.47	
WFD1929c	1	−4.2	0.45	
WFD1931	14	−2.8 ± 6.9	0.39 ± 0.24	5
WFD1933b	1	0.1	0.24	
WFD1935	2	−3.5 ± 4.0	0.16 ± 0.66	
WFD1948	2	6.0 ± 2.1	3.16 ± 2.56	6
WFD1949a	1	−1.1	−0.03	
WFD1949b	2	2.3 ± 3.1	−0.40 ± 0.20	7
WFD1951a	1	3.0	0.43	
WFD1953	6	−0.2 ± 1.2	0.20 ± 0.46	8
WFD1969	3	−2.2 ± 3.6	−0.12 ± 0.13	9
WFD1985	1	0.6	−0.48	
WFD1997	7	0.9 ± 2.9	0.34 ± 0.40	10
WFD2000	4	−0.1 ± 2.3	0.21 ± 0.39	
All transit circles	62	−0.7 ± 4.6	0.34 ± 0.84	11
TMA2003	10	−0.1 ± 0.5	−0.22 ± 0.36	12
All	92	−0.4 ± 4.1	0.24 ± 0.78	13

Notes.—(1) Considering only wide ($\rho > 5''.0$) systems, the mean ($N = 3$) residuals are $-0^\circ.6 \pm 1^\circ.3$ and $-0''.15 \pm 0''.19$. (2) Wide system ($N = 19$) residuals: $0^\circ.9 \pm 3^\circ.0$ and $0''.16 \pm 0''.42$. (3) Calibration data for close ($\rho < 5''.0$) system only. (4) Wide system ($N = 2$) residuals: $2^\circ.5 \pm 0^\circ.8$ and $0''.02 \pm 0''.13$. (5) Wide system ($N = 8$) residuals: $1^\circ.5 \pm 2^\circ.4$ and $0''.40 \pm 0''.25$. (6) Wide system ($N = 1$) residuals: $8^\circ.0$ and $5''.69$. (7) Wide system ($N = 1$) residuals: $-0^\circ.8$ and $-0''.20$. (8) Wide system ($N = 5$) residuals: $-0^\circ.0 \pm 1^\circ.2$ and $0''.12 \pm 0''.45$. (9) Wide system ($N = 2$) residuals: $0^\circ.2 \pm 1^\circ.3$ and $-0''.07 \pm 0''.13$. (10) Wide system ($N = 3$) residuals: $1^\circ.3 \pm 2^\circ.7$ and $0''.16 \pm 0''.40$. (11) Wide system ($N = 41$) residuals: $0^\circ.1 \pm 3^\circ.2$ and $0''.33 \pm 1''.01$. (12) Wide system ($N = 8$) residuals: $-0^\circ.1 \pm 0^\circ.5$ and $-0''.12 \pm 0''.32$. (13) Wide system ($N = 68$) residuals: $0^\circ.3 \pm 3^\circ.0$ and $0''.24 \pm 0''.85$.

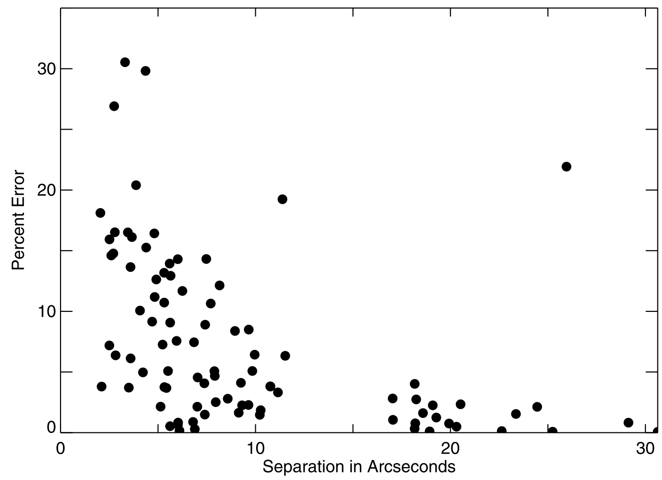

Fig. 6.—Separation vs. percent error in separation $[|(O - C)_\rho|/\rho]$ for the measures listed in Table 3. At about 10″ the error drops to ∼10%.

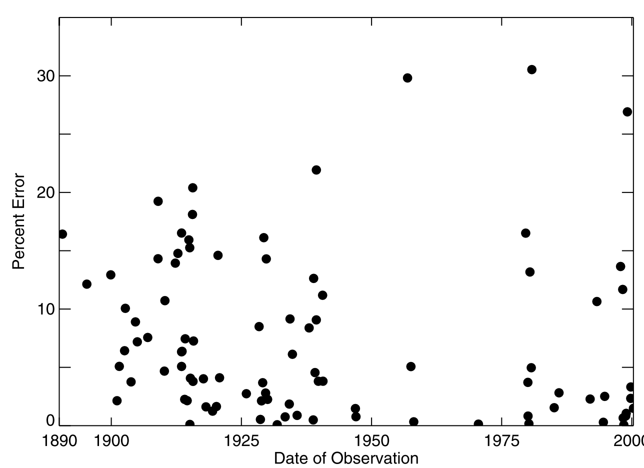

Fig. 7.—Date of observation vs. percent error in separation $[|(O - C)_\rho|/\rho]$ for the measures listed in Table 3. While the error seems to be increasing with time, this is primarily due to closer systems being measured.

TABLE 5
NEW WFC DOUBLES

WDS or α, δ (J2000.0) (1)	Discovery Designation (2)	Observation First (3)	Observation Last (4)	N (5)	Position Angle First (6)	Position Angle Last (7)	Separation First (8)	Separation Last (9)	Magnitude Primary (10)	Magnitude Secondary (11)
00099+7329	WFC 1	1897	2000	5	30	36	7.1	6.4	10.38	10.41
00249−7716	WFC 246	1894	1926	2	187	232	52.4	101.0	3.5	12.7
00251−8050	WFC 2	1896	1999	7	137	139	6.2	6.0	10.81	10.92
00429+8002	WFC 3	1897	2003	5	332	320	3.4	4.3	10.35	11.32
00453+6801	WFC 4	1892	2003	5	336	334	4.3	4.5	10.78	11.80
00593+7712	WFC 5	1897	1999	4	77	76	3.3	2.8	10.88	12.07
01151+3125	WFC 248	1903	2002	6	5	9	10.2	10.6	11.73	11.73
01328+6911	WFC 6	1894	2000	4	222	232	4.0	4.5	12.32	12.52
01452+3011	WFC 249	1903	2001	4	97	95	9.7	10.3	12.06	12.18
02045+4750	WFC 7	1898	1998	7	104	121	5.3	5.3	10.00	10.32

NOTE.—Table 5 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

TABLE 6
WFC CONTRIBUTIONS TO DOUBLE STAR WORK

Relative WFC Contribution	Number of Systems
WFC <1% of total	83
1% $\leq$ WFC < 10%	1316
10% $\leq$ WFC < 50%	15481
WFC $\geq$ 50%	30127

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